

SELF-STABILIZED ELECTROPHORETICALLY FRUSTRATED TOTAL INTERNAL REFLECTION DISPLAY

Reference to Related Application

- 5 **[0001]** This application claims the benefit of United States Provisional Patent Application Serial No. 60/399,168 filed 30 July 2002.

Technical Field

- 10 **[0002]** This invention improves the long-term stability of image displays which electrophoretically frustrate total internal reflection (TIR).

Background

- 15 **[0003]** It is known that images can be displayed by controllably frustrating TIR to switch selected pixels of a multi-pixel display between a reflective state in which light incident on those pixels undergoes TIR, and a non-reflective state in which TIR is frustrated at those pixels. It is also known that electrophoresis can be used to controllably frustrate TIR and controllably switch the state of pixels in such displays.
- 20 Electrophoresis is a well-known phenomenon whereby an electrostatically-charged species moves through a medium due to the influence of an applied electric field. For example, an electromagnetic field can be controllably applied to move particles through an electrophoretic medium toward or away from an evanescent wave region to frustrate
- 25 TIR at selected pixel portions of the region.

- 30 **[0004]** It is also known that repeated switching of a display which utilizes electrophoretically-mobile particles can result in a non-uniform distribution or clustering of the particles, gradually deteriorating the quality of images produced by the display over time. See for example Dalisa, A., "Electrophoretic Display Technology," IEEE Transactions on Electron Devices, Vol. 24, 827-834, 1977; and Müräu *et al*, "The understanding and elimination of some suspension instabilities in an electrophoretic display," J. Appl. Phys., Vol. 49, No. 9, September

1978, pp. 4820-4829. It has been shown that such undesirable clustering can be reduced by encapsulating groups of suspended particles in separate micro-fluidic regions. See for example Nakamura *et al*, "Development of Electrophoretic Display Using Microencapsulated Suspension," Society for Information Display Symposium Proceedings, 1014-1017, 1998 and Drzaic *et al*, "A Printed and Rollable Bistable Electronic Display," Society for Information Display Symposium Proceedings, 1131-1134, 1998.

10 Summary of Invention

[0005] This invention improves the long-term image stability of an electrophoretically-mobile particle display, by providing a thermodynamically stable agglomeration of particles in the electrophoretic suspension. The agglomeration can be electrophoretically moved as a substantially unitary whole to switch the display's pixels between reflective and non-reflective states, without encapsulating groups of suspended particles in separate regions.

Brief Description of Drawings

20 [0006] Figure 1 is a fragmented, cross-sectional view, on a greatly enlarged scale, of a portion of a prior art electrophoretically frustrated TIR image display, depicting undesirable non-uniform particle distribution.

[0007] Figure 2A is a fragmented, cross-sectional view, on a greatly enlarged scale, of a portion of a prior art electrophoretically frustrated TIR image display, before application of an electric field. Figure 2B depicts the Figure 2A display after selective application of an electric field.

[0008] Figure 3A is a fragmented, cross-sectional view, on a greatly enlarged scale, of a portion of one pixel of an electrophoretically frustrated TIR image display in accordance with the invention,

before application of an electric field. Figure 3B depicts the Figure 3A display after selective application of an electric field.

Description

5 [0009] Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the
10 invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0010] Figure 1 depicts a portion of an electrophoretically-frustrated TIR image display 10 having a transparent front sheet 12 and a rear sheet 14 substantially parallel to and spaced from front sheet 12.
15 Front sheet 12's inward surface is microstructured by forming a large plurality of parallel, reflective micro-prisms 16 thereon. Alternatively, front sheet 12's inward surface can be microstructured by forming a large plurality of approximately hemispherical high refractive index transparent hemi-beads thereon, as described in United States Patent
20 Application Serial No. 10/086,349 filed 4 March 2002, which is incorporated herein by reference. A thin, continuous, transparent electrode 18 is applied to the inward surfaces of prisms 16. A segmented electrode 20 is applied to the inward surface of rear sheet 14, to apply separate voltages (corresponding to individual pixels) between each
25 adjacent pair of prisms 16. There need not be a 1:1 correspondence between each pixel and one of prisms 16 or one of the segments of electrode 20; each pixel preferably corresponds to a plurality of prisms 16 and to a (possibly different) plurality of segments of electrode 20. An electrophoresis medium 22, for example, a low refractive index,
30 low viscosity, electrically insulating liquid such as Fluorinert™ perfluorinated hydrocarbon liquid available from 3M, St. Paul, MN substan-

tially fills the space between sheets 12, 14 forming a TIR interface between sheet 12 and medium 22. A finely dispersed suspension of non-light-scattering, light-absorptive particles 24, such as pigment particles, is provided in medium 22.

- 5 **[0011]** A voltage source (not shown) is electrically connected between electrodes 18, 20 to controllably apply a voltage across selected pixel regions of medium 22. Application of a voltage across a selected pixel region electrophoretically moves particles 24 suspended within the selected region to form a layer that begins within about 0.25
10 micron of the evanescent wave zone adjacent the inward surfaces of the selected region's prisms 16 and extends about 5 microns into the region. When electrophoretically moved as aforesaid, particles 24, which have a higher refractive index than the surrounding fluid and are much smaller than a wavelength of light and therefore substantially non-light-
15 scattering, cause the layer to have an effective refractive index that is substantially higher than that of the surrounding liquid. This absorptive particle layer has both a real component of the refractive index that frustrates TIR and causes transmission, rather than reflection, of the light ray at the interface; and an imaginary component that causes
20 absorption of the light ray at it passes through the absorptive particle layer. There is essentially no scattering of the light as it interacts with the particles, but rather the light is absorbed. This gives the selected pixel region a dark appearance to an observer who looks at sheet 12's outward surface. Application of an opposite polarity voltage across the
25 selected pixel region electrophoretically moves particles 24 toward that region's electrode 20, such that incident light rays which pass through sheet 12 are reflected by TIR at that region's TIR interface, giving the region a "white" appearance to an observer who looks at sheet 12's outward surface.
- 30 **[0012]** Further details of the construction and optical characteristics of electrophoretically-frustrated TIR image displays can be found

in United States Patent Nos. 6,064,784; 6,215,920; 6,304,365; 6,384,979; 6,437,921; and 6,452,734 all of which are incorporated herein by reference; and, in the aforementioned United States Patent Application Serial No. 10/086,349.

5 [0013] Electrophoretically-frustrated display 10 can exhibit undesirable clustering of particles 24 over time. More particularly, particles 24 tend to form loose agglomerates 26, surrounded by regions 28 of medium 22 containing relatively few suspended particles 24. Such clustering often results in long-term deterioration of the display's
10 image quality and overall performance.

[0014] Figures 2A and 2B depict a prior art technique for reducing undesirable particle clustering in an electrophoretically-frustrated display 30 having a transparent front sheet 32 and a rear sheet 34. Front sheet 32's inward surface is microstructured by forming a large
15 plurality of parallel, reflective micro-prisms 36 thereon. The apices 38 of micro-prisms 36 are connected to rear sheet 34's inward surface, forming an encapsulated channel 40 between the opposed facets of each adjacent pair of prisms 36. Each channel 40 is filled with an electrophoresis medium 42, forming a TIR interface between sheet 32 and
20 medium 42. Within each channel 40, medium 42 contains a finely dispersed suspension of non-light-scattering light-absorptive particles 44, such as pigment particles. Within each channel 40, a thin transparent electrode 45 is applied to the inward surfaces of the adjacent prisms 36 which define that channel. A segmented electrode 46 is
25 applied to the inward surface of rear sheet 34, to create separate pixel regions corresponding to each channel 40 (or corresponding to a selected group of adjacent channels 40).

[0015] A voltage source (not shown) is electrically connected between each channel's electrode pair 45, 46 to controllably apply a
30 voltage across the corresponding pixel region. Application of a voltage across a selected pixel region electrophoretically moves particles 44

suspended within the selected region to form a layer that begins within about 0.25 micron of the evanescent wave zone adjacent the inward surfaces of the selected region's prisms 16 and extends about 5 microns into the region, as depicted in the case of channel 40C (Figure 2B).

5 When electrophoretically moved as aforesaid, particles 44, which have a higher refractive index than the surrounding fluid and are much smaller than a wavelength of light and therefore substantially non-light-scattering, cause the layer to have an effective refractive index that is substantially higher than that of the surrounding liquid. This absorptive
10 particle layer has both a real component of the refractive index that frustrates TIR and causes transmission, rather than reflection, of the light ray at the interface; and an imaginary component that causes absorption of the light ray at it passes through the absorptive particle layer. There is essentially no scattering of the light as it interacts with
15 the particles, but rather the light is absorbed. This gives the selected pixel region a dark appearance to an observer who looks at sheet 32's outward surface. Application of an opposite polarity voltage across a selected pixel region electrophoretically moves (i.e. switches) particles 44 toward that region's electrode 46, as depicted in the case of channels
20 40A and 40B, such that light rays 52, 54 which pass through sheet 32 are reflected by TIR at that region's TIR interface, giving the region a "white" appearance to an observer who looks at sheet 32's outward surface.

[0016] Although encapsulation of groups of particles 44 within
25 separate channels 40 reduces undesirable clustering, it may in some cases be impractical to fabricate, fill or maintain channels 40.

[0017] In accordance with the invention, the electrophoresis medium contains a high concentration of light-absorptive pigment particles, forming a sponge-like electrophoretic suspension paste having
30 a volume fraction of particles in the suspension that is sufficiently large that the particles do not move freely within the electrophoresis medium,

thus preventing the lateral particle motion which is believed to cause long-term particle clustering. More specifically, the volume fraction is sufficiently large that the suspension is in a thermodynamically stable state such that a uniform distribution of particles is maintained. The
5 volume fraction at which this thermodynamic stability occurs depends on the inter-particle force relationship for the specific particles within the particular suspension. The suspension can be formed by adding particles to the electrophoresis medium until the particles form a substantially unitary agglomeration which can be electrophoretically
10 moved and compressed as a substantially unitary whole in response to an applied voltage, to controllably frustrate TIR. Alternatively, a dilute suspension can be initially formed, followed by evaporation of the electrophoresis medium until the desired volume fraction of particles in the suspension is attained. A dispersant such as Krytox™ 157-FSL,
15 Krytox™ 157-FSM or Krytox™ 157-FSH fluorinated oil (respectively having specified molecular weights of approximately 2500, 3500-4000 and 7000-7500, CAS Registry No. 860164-51-4, DuPont Performance Lubricants, Wilmington, DE 19880-0023) is preferably added to the suspension to facilitate stable suspension of the particles in the electro-
20 phoresis medium.

[0018] This is shown schematically in Figures 3A and 3B, which depict a selected pixel region of the Figure 1 display structure with an electrophoretic suspension having an electrophoretically compressible, non-light-scattering light absorbing particle agglomeration 56 substituted
25 for electrophoresis medium 22 and particles 24. A voltage source 57 is electrically connected between electrodes 18, 20 to controllably apply a voltage across electrophoresis medium 22. The applied voltage affects substantially all particles 24 between electrodes 18, 20 (i.e. particle agglomeration 56). As shown in Figure 3A, the applied voltage electro-
30 phoretically compresses particle agglomeration 56 away from electrode 18 toward electrode 20. This leaves a thin region 58 of low refractive

index electrophoretic fluid between the inward surface of sheet 12 and particle agglomeration 56, which is sufficiently thick that it enables substantially all of the evanescent wave to be confined to a particle-free region of fluid and thus causes TIR, such that light ray 60 which passes through sheet 12 is reflected by TIR at the depicted region's TIR interface, giving the region a "white" appearance to an observer who looks at sheet 12's outward surface.

[0019] More particularly, particles 24 are substantially incompressible, but particle agglomeration 56 has many tiny inter-particle voids containing electrophoresis medium 22. Since particles 24 are electrostatically charged as a result of chemical interactions between the solvent and dispersant molecules and surface groups on the particles, application of a voltage across particle agglomeration 56 moves particles 24 as a substantially unitary whole toward one or the other of electrodes 18, 20 depending on the polarity of the applied voltage. This compresses particle agglomeration 56, packing particles 24 even more tightly together and forcing electrophoresis medium 22 out of the inter-particle voids.

[0020] As shown in Figure 3B, application of an opposite polarity voltage across the depicted pixel region electrophoretically compresses (i.e. switches) particle agglomeration 56 away from electrode 20 toward electrode 18, to within about 0.25 micron of the evanescent wave zone adjacent the inward surfaces of the depicted region's prisms 16. When electrophoretically compressed toward electrode 18 as aforesaid, particle agglomeration 56 scatters or absorbs incident light ray 62 by causing a refractive index mismatch which frustrates TIR, giving the depicted pixel region a dark appearance to an observer who looks at sheet 12's outward surface.

[0021] It is counterintuitive that the large volume fraction of particles 24 in the suspension allows sufficient motion of particles 24 within the evanescent wave region to controllably modulate TIR.

Although the large volume fraction of particles 24 in the suspension gives the suspension high bulk viscosity, the low refractive index electrophoresis medium 22 filling the inter-particle voids has very low viscosity, and thus it is comparatively easy to compress particle
5 agglomeration 56 to force a region of particle-free low refractive index electrophoresis medium 22 into contact with the inward surface of sheet 12. More specifically, since the viscosity of electrophoresis medium 22 is low and since the particle-free region need only be thick enough to confine substantially all of the evanescent wave, good optical control
10 can be maintained.

[0022] Electrode 20 can be segmented to provide a plurality of electrode segments, as shown in Figure 1. A suitable controller (not shown) can then be used to apply a first voltage between the first electrode and a first one of the electrode segments, apply a second
15 voltage between the first electrode and a second one of the electrode segments, etc. in order to establish distinct electric fields between selected electrodes. Each electrode segment (or group of adjacent electrode segments) corresponds to an individually controllable pixel.

[0023] As will be apparent to those skilled in the art in light of the
20 foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example, as previously explained, the volume fraction of particles 24 in the suspension should be sufficiently large that the suspension is in a thermodynamically-stable state such that a uniform
25 distribution of particles is maintained. The volume fraction at which this thermodynamic stability occurs depends on the inter-particle force relationship for the specific particles within the particular suspension. For many suspensions this thermodynamic stability occurs within the range of about 25% to 75%, with efficacy improving as the volume
30 fraction of particles 24 is increased within the foregoing range. Electrophoresis medium 22 and the dispersant constitute the remaining volume

fraction of particle agglomeration 56 which is not occupied by particles 24. Higher volume fractions of particles 24 in the suspension (within the aforementioned range) reduce the likelihood of particles 24 clustering together after repeated switching. But, if the volume fraction of particles 24 in the suspension is greater than about 75%, insufficient electrophoresis medium 22 remains in the inter-particle voids, making it difficult to attain the highly reflective state by compressing particle agglomeration 56 and forcing a sufficient quantity of electrophoresis medium 22 out of the inter-particle voids to form low refractive index electrophoretic fluid region 58. The desired compressibility of particle agglomeration 56 is also impaired if insufficient dispersant is provided in the suspension, resulting in non-stable suspension of particles 24 which can cause particles 24 to adhere to one another. The scope of the invention is to be construed in accordance with the substance defined by the following claims.